

## **FRONT-END CIRCULATOR FOR AN OPTICAL DEVICE**

### **CROSS-REFERENCE TO RELATED APPLICATIONS**

[01] The present application claims priority from United States Patent Application 60/506,176 filed December 20, 2003, which is incorporated herein by reference for all purposes.

### **TECHNICAL FIELD**

[02] The present invention relates to an optical circulator, and in particular to an optical circulator positioned at the front end of an optical device for launching an optical signal into the optical device and for redirecting the optical signal after modification by the optical device.

### **BACKGROUND OF THE INVENTION**

[03] Conventional circulators, such as those disclosed in United States Patents Nos. 5,574,596 issued November 12, 1996 to Yihao Cheng; and 5,909,310 issued June 1, 1999 to Wei-Zhong Li et al are three port devices that direct light entering a first port to a second port, and light entering the second port back to a third port. Generally, the light entering the first port is divided into two sub-beams, the polarization of which is manipulated to enable the sub-beams to pass through a polarization-dependent beam director along a first path, after which the sub-beams are recombined for output. Similarly, light entering the second port is divided into two sub-beams, but the polarization thereof is manipulated so that the sub-beams pass through the polarization-dependent beam director along a second path, different than the first, whereby the sub-beams are recombined at the third port.

[04] Unfortunately, these conventional circulators are designed to recombine the light beam traveling from the first port to the second port, and to receive a combined light beam at the second port for travel to the third port.

[05] An object of the present invention is to overcome the shortcomings of the prior art by providing an optical circulator that outputs and receives like-polarized sub-beams instead of a single combined beam at the second port.

### **SUMMARY OF THE INVENTION**

[06] Accordingly, the present invention relates to a circulator device for launching on optical signal into an optical device and for outputting the optical signal after modification by the optical device comprising:

- [07] an input port for inputting the optical signal;
- [08] a polarization beam splitter optically coupled to the input port for separating the optical signal into first and second orthogonally polarized sub-beams;
- [09] a first polarization rotator for rotating the polarization of at least one of the first and second orthogonally polarized sub-beams of the optical signal, so that both sub-beams of the optical signal have the same polarization;
- [10] polarization beam directing means for directing optical sub-beams with a first polarization along one set of paths, and for directing optical sub-beams with a second polarization along another set of paths;
- [11] non-reciprocal polarization rotating means for rotating the polarization of optical sub-beams traveling in a first direction therethrough, while having no overall effect on the polarization of optical sub-beams traveling in a second direction therethrough;
- [12] a first input/output port for outputting the first sub-beam of the optical signal with the first polarization, and for inputting a first sub-beam of the modified optical signal with the first polarization, whereby the first sub-beam of the modified optical signal travels back through the non-reciprocal polarization rotating means and the polarization beam directing means;
- [13] a second input/output port for outputting the second sub-beam of the optical signal with the first polarization, and for inputting a second sub-beam of the modified optical signal with the first polarization, whereby the second sub-beam of the modified optical signal travels back through the non-reciprocal polarization rotating means and the polarization beam directing means;
- [14] a second polarization rotator for rotating the polarization of at least one of the first and second sub-beams of the modified optical signal, so that the sub-beams of the optical signal have orthogonal polarizations;
- [15] a polarization beam combiner optically coupled to the output port for combining first and second orthogonally polarized sub-beams of the modified optical signal; and
- [16] an output port for outputting the modified optical signal;
- [17] whereby light entering the first and second input/output ports with the second polarization will be directed away from the input and output ports.

**BRIEF DESCRIPTION OF THE DRAWINGS**

[18] The invention will be described in greater detail with reference to the accompanying drawings which represent preferred embodiments thereof, wherein:

[19] Figure 1 is a plan view of the circulator according to the present invention illustrating light traveling from a first port to a third and fourth ports;

[20] Figure 2 is a plan view of the circular of Fig. 1 illustrating light traveling from the third and fourth ports to a second port;

[21] Figure 3 is a side of the circulator of Figs. 1 and 2 illustrating light traveling from the first port to the third and fourth ports, and from the third and fourth ports to the second port;

[22] Figure 4 is a chart of the polarizations of sub-beams of light traveling through the various elements of the circulator of Figs. 1 to 3;

[23] Figure 5 is a schematic representation of an optical device platform utilizing the circulator of Figs. 1 to 3;

[24] Figure 6 is a plan view of an alternative embodiment of the present invention;

[25] Figure 7 is a side view of the embodiment of Fig. 5;

[26] Figure 8 is an exploded isometric view of the circulator of Figs 5 and 6 illustrating light traveling from the first port to the third and fourth ports;

[27] Figure 9 is an exploded isometric view of the circulator of Figs 5, 6 and 7 illustrating light traveling from the third and fourth ports to the second port; and

[28] Figure 10 is a chart of the polarizations of sub-beams of light traveling through the various elements of the circulator of Figs. 5 to 8.

**DETAILED DESCRIPTION**

[29] With reference to Figures 1 to 4, the circulator 1 according to the present invention includes a first port 2 and a second port 3 adjacent each other on one end. The first port 2 launches a beam of light 4 into a first birefringent walk-off crystal 6 (Position A in Fig. 4), which splits the beam of light 4 into two orthogonally polarized sub-beams 7 and 8 (Position B). Sub-beam 7 travels through a first half-wave plate 9, disposed with a birefringent axis at  $+22.5^\circ$ , for rotating the polarization of the sub-beam 7 by  $+45^\circ$ . The birefringent axis of a second half-

wave plate 11 is oriented at  $-22.5^\circ$  for rotating the polarization of the sub-beam 8 by  $-45^\circ$ , whereby both sub-beams 7 and 8 have the same polarization (Position C). A first Faraday rotator 12 is positioned adjacent the first and second waveplates 9 and 11 for rotating the polarization of the sub-beams 7 and 8 by another  $+45^\circ$ , whereby both sub-beams 7 and 8 are horizontally polarized (Position D). The horizontally polarized sub-beams 7 and 8 pass through a second birefringent walk-off crystal 13, which directs the sub-beams according to their polarization. Since the sub-beams 7 and 8 are horizontally polarized, they travel straight through the second birefringent walk-off crystal 13 (Position E). A second Faraday rotator 14 rotates the polarization of both sub-beams 7 and 8 by  $+45^\circ$  (Position F), and a third half-wave plate 16 rotates both of the sub-beams 7 and 8 by  $-45^\circ$  (Position G), whereby the combination of the second Faraday rotator 14 and the third half-wave plate 16 have no cumulative effect on the polarization of the sub-beams 7 and 8. A third port 17 is provided for outputting the sub-beam 7, while a fourth port 18 is provided for outputting the sub-beam 8.

[30] With reference to Figure 5, the present invention was designed for use as the circulator front end 1 for an optical device platform 22, which can be used for various devices, e.g. a wavelength switch or a dynamic gain equalizer. Within the platform 22 the sub-beams 7 and 8 are directed at a focusing and redirecting element in the form of a concave mirror 23, which reflects the sub-beams 7 and 8 towards a wavelength dispersive element 24. The wavelength dispersive element 24 separates each sub-beam 7 and 8 into a set of distinct wavelength channel sub-beams 27a to 27g and 28a to 28g, respectively, and directs the wavelength channel subbeams 27a to 27g and 28a to 28g towards the concave mirror 23 for a second refocusing and reflection. Subsequently, the wavelength channel sub-beams 27a to 27g and 28a to 28g are directed at a modifying element 29, which can be in the form of a micro-electro-mechanical (MEMs) mirror array for the wavelength switch or an array of liquid crystal cells for the dynamic gain equalizer. The MEMs mirror array would redirect one or more pairs of the wavelength channel sub-beams, e.g. 27b and 28b, 27c and 28c, along a different path, while the remaining wavelength channel sub-beams 27a, 28a, 27d to 27g and 28d to 28g are reflected back to the dispersive element 24 via the concave mirror 23 for recombination into sub-beams 7' and 8'. The recombined sub-beams 7' and 8' are reflected via the concave mirror 23 to the front-end circulator 1.

[31] Alternatively, if the modifying element 29 is an array of liquid crystal cells, the polarizations of the various wavelength channel sub-beams 27a to 27g and 28a to 28g are independently rotated by desired amounts, depending on the amount of attenuation that is required. Accordingly, when the wavelength channel sub-beams 27a to 27g and 28a to 28g pass

through any polarization beam splitter an amount of unwanted light can be separated from the remaining beams. This separation can be done in the modifying element 29 or at the circulator front end 1.

[32] With reference to Figures 2 and 3, the recombined sub-beams 7' and 8' re-enter the third and fourth ports 17 and 18, respectively, (Position G'), and pass through the third half-wave plate 16 and the second Faraday rotator 14. Since the third half-wave plate 16 is a reciprocal polarization rotator, the polarization of both sub-beams 7' and 8' is rotated by  $+45^\circ$  (Position F'); however, since the second Faraday rotator 14 is a non-reciprocal polarization rotator, the polarization of both sub-beams 7' and 8' is rotated by another  $+45^\circ$  for a combined total of  $+90^\circ$ , e.g. from horizontally to vertically polarized (Position E'). As a result, the sub-beams 7' and 8' get walked off by the second birefringent walk-off crystal 13. Up until now the sub-beams 7, 8, 7' and 8' have traveled in the same plane, illustrated in Figure 1 and the upper path in Figure 3, through the circulator 1; however, because the birefringent axis of the second birefringent walk-off crystal 13 is perpendicular to the birefringent axis of the first birefringent walk-off crystal 6, the second birefringent walk-off crystal 13 redirects the sub-beams 7' and 8' out of the original plane to a parallel plane, illustrated in Figure 2 and the lower path in Figure 3 (Position D').

[33] The sub-beam 7', traveling in the opposite direction to sub-beam 7, passes through the first Faraday rotator 12 ( $+45^\circ$ ) and the first half-wave plate 9 ( $-45^\circ$ ), which results in no cumulative effect to the polarization thereof, e.g. stays vertically polarized (Position B'). The sub-beam 8' passes through the Faraday rotator 12 ( $+45^\circ$ ) and the second half-wave plate 11 ( $+45^\circ$ ), which rotates the polarization of the sub-beam 8' ( $+90^\circ$ ) from vertically to horizontally polarized (Position B'). Accordingly, the sub-beam 7' is walked off by the first walk-off crystal 6, towards the sub-beam 8', which passes straight through the first walk-off crystal 6. The recombined beam of light 4' is then output the second port 3 (Position A').

[34] With reference to the bottom row of Figure 4, any vertically polarized light 7'' and 8'' re-entering the third and fourth ports 17 and 18, respectively, (Position G''), will pass through the third half-wave plate 16 ( $+45^\circ$ ) and the second Faraday rotator 14 ( $+45^\circ$ ), resulting in a change in the state of polarization of  $+90^\circ$ , e.g. vertically to horizontally polarized (Position E''). The horizontally polarized light 7'' and 8'' will not be walked off to the lower plane by the second birefringent walk-off crystal 13, but will pass therethrough in the original (upper) plane (Position D''). The first Faraday rotator 12 ( $+45^\circ$ ) and the first half-wave plate 9 ( $-45^\circ$ ) have no cumulative effect on the polarization of the sub-beam 7'', which stays horizontally

polarized (Position B''). The first Faraday rotator 12 (+45°) and the second half-wave plate 11 (+45°) rotate the polarization of the sub-beam 8'' by 90° from horizontally polarized to vertically polarized (Position B''). Accordingly, the sub-beam 7'' passes straight through the first birefringent walk-off crystal 6, while the sub-beam 8'' gets walked off away from the sub-beam 7''. Neither sub-beam 7'' or 8'' gets directed to the input port 2 or the output port 3, i.e. both sub-beam 7'' and 8'' are spilled off.

[35] An alternative embodiment, for use in collimated space, is illustrated in Figures 6 to 10. An input port 31 comprises a ferrule 32 surrounding an end of an input fiber 33, which launches a beam of light 34 into a GRIN lens 36 (Position I). A polarization beam splitter in the form of a first birefringent crystal 37 (Rutile or YVO<sub>4</sub>) divides the beam 34 into first and second orthogonally polarized sub-beams 38 and 39 (Position II). A first half-wave plate 41, with its birefringent axis oriented at +22.5°, rotates the polarization of the first sub-beam 38 by +45° (Position III), after which a first Faraday rotator 42 rotates the polarization of the first sub-beam 38 by an additional +45° (Position IV), whereby the polarization of the first sub-beam is rotated from horizontal to vertical. A second half-wave plate 43, with its birefringent axis oriented at -22.5°, rotates the polarization of the second sub-beam 39 by -45° (Position III), after which the first Faraday rotator 42 rotates the polarization of the second sub-beam 38 by +45° (Position IV), whereby the polarization of the second sub-beam 38 remains the same, e.g. vertically polarized. A polarization beam director, in the form of a polarization beam splitting prism 44 with a pair of polarization beam splitting coating 46a and 46b, redirects the vertically polarized first and second sub-beams 37 and 38 to a third half-wave plate 47 (Position V), with its birefringent axis oriented at +22.5°, which rotates the polarization of both sub-beams by +45° (Position VI). A second Faraday rotator 48 rotates the polarization of the first and second sub-beams 37 and 38 by a further +45°, whereby the first and second sub-beams are horizontally polarized for output the third and fourth ports 51 and 52 into the optical device platform (Position VII), as hereinbefore described.

[36] Modified sub-beams 37' and 38' re-entering the third and fourth ports 51 and 52, respectively, (Position VIII) pass back through the second Faraday rotator 48, which again rotates their polarization by +45° (Position IX). The third half-wave plate 47 negates the aforementioned polarization rotation by rotating the polarization of the modified sub-beams 37' and 38' by -45°, whereby the modified sub-beams 37' and 38' re-enter the polarization beam splitting cube 44 horizontally polarized (Position X), instead of vertically polarized, as before. Accordingly, the modified sub-beams 37' and 38' pass directly through the polarization beam splitting coating 46b to a third Faraday rotator 53 (Position XI), which rotates the polarization of

both modified sub-beams 37' and 38' by  $-45^\circ$  (Position XII). A fourth half-wave plate 54 rotates the polarization of the first modified sub-beam 37' by a further  $-45^\circ$ , whereby the first modified sub-beam 37' becomes vertically polarized (Position XIII). A fifth half-wave plate 56 negates the effect of the third Faraday rotator 49 by rotating the polarization of the second modified sub-beam 38' by  $+45^\circ$ , whereby the second modified sub-beam 38' remains horizontally polarized (Position XIII). A single magnet 57 is provided for use with all three Faraday rotators 42, 47 and 49.

[37] A polarization beam combiner, in the form of a second birefringent walk-off crystal 58, recombines the first and second modified sub-beams 37' and 38' into a single beam 34' for output the output port 59. A second GRIN lens 61 focuses the beam 34' onto an output fiber 62, which is encased in a ferrule 63.